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Changes in soil carbon stocks across the Forest-Agroforest-Agriculture/Pasture continuum in various agroecological regions: A meta-analysis

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ABSTRACT

The contribution of agroforestry systems (AFS) to enhance soil organic carbon (SOC) storage in soil layers due to the presence of deep tree roots are of interest in the context of promoting carbon sinks and greenhouse gas mitigation. To quantify the relative soil C contribution from trees in agroforestry systems (AFS), this study assessed the reported differences in SOC stocks under agroforestry systems in comparison with other land-use systems (Agriculture, Forestry, Pasture, or Uncultivated Land) in various soil-depth classes in four agroecological regions (arid and semiarid, ASA; lowland humid tropics, LHT; Mediterranean, MED; and temperate, TEM) around the world. Using mixed-effect models and a meta-analytical approach, we synthesized data from 78 peer-reviewed studies that generated 858 data points (sites) on SOC stock under various AFS practiced globally. Comparing Agroforest vs. Agriculture or Agroforest vs. Pasture, SOC stocks under AFS were higher by +27% in the ASA region, +26% in LHT, and +5.8% in TEM, but –5.3% in the TEM in the 0–100 cm soil depth. The Agroforest aged between 10–20 years had higher SOC stock than newly established, as well as < 10-year-old systems across all soil-depth classes and agroecological regions. Overall, Agroforest vs. Agriculture land management practices resulted in positive SOC stock changes within AFS up to 100 cm soil depth, whereas SOC stock under AFS was lower than under Forest. The results suggest that a general pattern of Forest – Agroforest – Agriculture – Pasture continuum could be expected in SOC stock decline during land-use changes. Improvement of SOC stocks under AFS varied across agroecological regions, the highest being under arid and semiarid region, closely followed by the low humid tropics. The important outcome of this meta-analysis is worthy of emphasizing of the role of AFS in climate change adaptation and greenhouse gas mitigation strategies by promoting carbon sinks.

1. Introduction

Ecosystems can act as carbon (C) sinks by capturing and storing significant amounts of atmospheric carbon dioxide (CO_2) in biomass and in the soil. Tree-based land-use systems such as agroforestry are reported to have the potential to enhance C sequestrationboth above- and below ground (Nair et al., 2009, 2010). The importance of managing such systems through appropriate agroecological (carbon) farming methods is increasingly being recognized as a promising strategy for enhancing soil carbon sequestration (Toensmeier, 2016). Indeed, agroforestry has figured prominently in the deliberations and action plans related to climate change adaptation and mitigation and environmental protection at various international, national, regional forums (Sinclair, 1999; Tubiello, 2012). Although several studies on C sequestration under AFS are reported in the literature, they are highly variable in the study procedures as well as the nature of systems and study locations such that the results lack the needed quantitative rigor. This makes it difficult to extrapolate them to broader contexts of systems and locations outside the specific locations of the individual studies. The objective of this study was to undertake a statistically rigorous, quantitative assessment of the scattered results on soil organic carbon (SOC) stocks reported under various AFS, in comparison with those in agricultural, forestry, and pasture systems in different agroecological regions around the world through a meta-analytical approach.

Given that intentional integration of trees in agricultural (crop and livestock) systems is the fundamental attribute of agroforestry systems (Nair, 1993), AFS offer greater opportunities than monocultural (single-component) agricultural systems for capture and storage of atmospheric CO_2 in biomass and soils (Luedeling et al., 2014; Mbow et al., 2014). This has been attributed to several reasons including efficient C (and

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nutrient) cycling within the soil–plant system, increased return of biomass C to soil, decreased biomass decomposition and soil organic matter (SOM) destabilization in the tropics, and sequestration of soil C in deeper layers of soil (Montagnini and Nair, 2004; Nair, 2012; Nair and Nair, 2014; Oelbermann and Voroney, 2011; Saha et al., 2010; Tonucci et al., 2011).

Since the beginning of realization of the importance of carbon sequestration (i.e., capture and storage of atmospheric CO_2 in long lived pools: UNFCC, 2006), in climate-change mitigation and adaptation, a large body of scientific literature has accumulated on C sequestration under land-use systems; AFS are no exception. Nair et al. (2010) referenced most of such publications in AFS; several others have appeared since; e.g., Abou Rajab et al., 2016; Cardinael et al., 2017; Jose and Bardhan, 2012; Lorenz and Lal, 2014; Post and Kwon, 2000; Upson et al., 2016; Kim et al., 2016; De Stefano and Jacobson, 2017; Feliciano et al., 2018. While many of these are based on biomass and soil sampling undertaken at a specified period, some are based on field measurements and simulation models based, naturally, on various assumptions and reports; and, almost all of them report the amount of SOC stocks under specific systems at the time of study. While these reports are extremely valuable to understand the existing conditions, they represent only one point in the continuum of land-use changes. They are inadequate to predict the rate of change in SOC with alterations in land management practices from agriculture to AFS (introducing trees into agricultural fields) or forest to AFS (converting forestlands into AFS by outright forest clearing and AFS establishment, or thinning existing forest and underplanting shade-tolerant specialty species). Such information is needed for properly assessing the benefits associated with the adoption of AFS in terms of economic advantages and incentives for local farmers. A meta-analysis, which is a statistical procedure for comparing and synthesizing results from different studies for finding common patterns, discrepancies, or other interesting relationships that may not be detectable from individual studies (Borenstein et al., 2009), provides a more comprehensive approach to attaining such information. When the treatment or effect size is consistent among studies, meta-analysis can be used to identify this common effect.

The effects of adopting alternative land management practices on SOC stocks and other ecosystem services in several land-use systems have been summarized through several meta-analyses (De Beenhouwer et al., 2013). Berthrong et al. (2009) evaluated how afforestation affected SOC along with other soil properties like N, pH, CEC across pine plantations; Guo and Gifford (2002) found SOC stocks declined after the conversion from pasture to plantation, native forest to crops, and pasture to crops. Reporting the results from a meta-analysis on the effect of cover crops on C sequestration in agricultural soils, Poeplau and Don (2015) suggested that cover crops significantly improved SOC stock by an average of 16.7 Mg C ha^{-1} over that of the reference croplands. A global meta-analysis conducted by Don et al. (2011) found that SOC losses could partly be reversible under tropical weathered soils. According to the authors, if agricultural land was afforested, SOC improved by 29%, and when cropland was converted to grassland, the increase was 26% for global land-use change in soil. In addition to such "general" meta-analyses that are relevant to AFS, three studies that are specific to AFS have also been reported recently (Kim et al., 2016; De Stefano and Jacobson, 2017; Feliciano et al., 2018). The analysis presented here entails a substantial improvement over those three AF-specific analyses in a number of ways including the use of larger number of data points, inclusion of most recent publication, coverage of broader and more diverse range of ecological regions, analyzing the effect of different age groups of AFS on SOC stocks, variation of SOC stocks up to a depth of 100 cm and adoption of more elaborate and rigorous statistical procedures. Recognizing the extreme location-specificity of AFS practiced around the world depending on biogeographic, ecological, and socioeconomic conditions, this study focuses on understanding the trend of SOC stock changes (ΔSOC) across Forest-Agroforest-Agriculture/Pasture continuum in different agroecological regions around the world where agroforestry is practiced.

2. Materials and methods

2.1. Data sources and categorization

We compiled data from the literature on the influence of AFS on soil carbon stocks and characterized each study according to the following categories: from forest to AFS, from pasture to AFS, from uncultivated land to AFS. The following relevant factors were also included in the compilation: agroecological region, age (time since AFS was adopted), climate data (precipitation and temperature) according to the Köppen climate classification (Köppen Classification System), soil bulk density, soil sampling depth from soil surface.

The research articles on AFS used for the analysis were selected from peer-reviewed publications found in *ISI Web of Science and Google Scholar*, based on a search with keywords (alone or in combinations): *agroforestry/ specific agroforestry system, soil organic carbon (SOC) stock, C sequestration, soil C stock, and soil C pool*. Only those reports that included data on soil C stocks were included. The selected research articles consisted of all three major groups of AFS (Agrisilviculture, Agrosilvopasture, and Silvopasture) according to Nair's (1985) classification; they were further organized into subgroups of AFS according to Nair (2014); thus, the dataset represented 15 AFS (Table 1). Non-agroforestry land-use practices (control) were grouped into four categories based on the information provided by the authors: (1) Agriculture, (2) Forest, (3) Pasture, and (4) Uncultivated Land. Uncultivated land was the term used in some publications to refer to barren/fallow land that was not under any distinguishably managed land-use systems as agriculture, forestry, or pasture.

The study included different types of AFS, from 30 countries across Asia, Africa, North America, Latin America, and Europe (Table 1), with a total of 858 data points (sites) from 78 published research articles. The data points refer to paired sites involving an AFS and a corresponding control (AFS vs Forest/Agriculture/Pasture/Uncultivated Land).The data points were categorized under four agroecological regions (Table 2) according to the Köppen climate classification (The Köppen Classification System). Each region had four types of AFS, except ASA which had three. The details of agroecological regions and AFS included are elaborated under Tables 2 and 3.The identified research articles were successively scrutinized by analysis of their abstracts following the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) (Appendix S1, Fig. S1), an evidence-based reporting tool used for systematic reviews and meta-analyses (Moher et al., 2009). The publications were then included in a preliminary list, which were further screened to select only those that had reported soil C concentration or stock per unit land area (Mg C ha^{-1} or equivalent),

Table 1
Number of data points across different agroecological regions and agroforestry systems included in the meta-analysis on soil organic carbon stocks.[a]

Agroforestry Systems/Agroecological regions	ASA	LHT	MED	TEM	Total (n)
Agrisilviculture	30	274	15	43	362
Agrosilvopasture	9	59	4	22	94
Silvopasture	67	65	25	45	202
Multistrata Systems	n.a.	168	n.a.	n.a.	168
Silvoarable Systems	n.a.	n.a.	27	1	28
Protective Systems	n.a.	n.a.	n.a.	4	4
Overall	106	566	71	115	858

Note: ASA = Arid and Semiarid; LHT = Lowland Humid Tropics and subtropics; MED = Mediterranean; TEM = Temperate agroecological regions respectively; n.a. = not available.

[a] The types of agroforestry systems have been elaborated in Appendix S1, Table S17.

Table 2
Agroecological features and system characteristics of various agroforestry systems included in the meta-analysis.

Agroecological region	Agroecological region (Köppen)	AFS practiced	Major soil types (Terms used in FAO system in italics)[a]	Latitude co-ordinate position
Arid and semiarid	Hot Desert (Bwh), Hot Semi-Arid (Bsh), Semi-Arid (Bsk, BSh), Cold Desert (BWk), Mild desert (BWn)	Agrisilviculture, Agrosilvopasture, Silvopasture	Aridisols. *Regosols*, Ferrasols, Lixisols	20 °N - 35 °N and S of the equator and in large continental regions of the mid-latitudes
Lowland Humid Tropics and subtropics)	Tropical Savanna (Aw), Tropical Rainforest (Af), Tropical Monsoon (Am), Subtropical (Cfa, Cwa)	Multistrata Systems, Agrisilviculture, Agrosilvopasture, Silvopasture	Oxisols, Ultisols, Alfisols, Vertisols, *Cambisols*	15 °N to 25 °N and 15 °S to 25 °S from the equator
Mediterranean	Hot Summer Mediterranean (Csa), Warm Summer Mediterranean (Csb), Cool Summer Mediterranean (Csc)	Agrisilviculture, Agrosilvopasture, Silvopasture, Silvoarable Systems	*Umbrisols, Vertosols, Luvisols*	Located on the western sides of continents between the latitudes of 30 °N and 45 °N
Temperate	Temperate (Cwb, Cwc, Cfb, Cfc), Continental (Dfa, Dfb), Humid Continental (Dfb)	Agrisilviculture, Agrosilvopasture, Silvopasture, Protective Systems	*Umbrisols, Luvisols, Vertosols, Spodosols,* Andosols	Located in latitudes between 40 °N and 60 °N

[a] Approximately equivalent terms in USDA Soil Taxonomy for the FAO soil terms listed are: *Acrisols* ~ Ultisols; *Cambisols* ~ Inceptisols; *Ferralsols* ~ Oxisols; *Luvisol* ~Alfisols; *Regosols* ~ Entisols.

for land-use comparisons (Agroforestry vs. Agriculture/Forestry/Pasture/Uncultivated land) with means and number of replicates. [In this paper, the terms Agriculture, Forestry, Pasture, Uncultivated Land, and types of Agroforestry are written with capital first letters when they are considered as experimental treatments and controls, but not when used in the general sense]. A list of the data sources is given as Appendix S2. If SD (standard deviation) values were missing from a study, other variance measures like standard error (SE) of means were used to calculate the SD, or error bars of the figures were used for SD estimation. The overall coefficient of variance (CV), without the missing SD, was generated and then multiplied with the means of missing SD to obtain the imputed SD. Additionally, the data sets were categorized according to the age of the AFS into four groups: 0–5, 5–10, 10–20, and > 20 years.

2.2. Site selection, soil-depth classes and SOC stock calculations

For the purpose of this meta-analysis, paired sites were chosen for further analysis. Paired sites allow a comparison between an AFS and an adjacent control site like Agriculture/Forest/Pasture/Uncultivated Land. Studies selected for the analysis had reported varying depth classes from 10 to 250 cm. Results of an initial analysis for the depth class below 100 cm (100–200 cm) showed the results were skewed because of the low number of data points. Therefore, soil depths up to 100 cm only were included in further analysis, and these were grouped into four soil-depth classes (all in cm):0–20, 0–40, 0–60, 60–100; and 0–100. All the included research articles, however, did not have all these depth classes, and had not reported SOC stocks in those distinct depth-classes. Nevertheless, the studies were categorized according to the above-mentioned depth classes as best as possible. For example, if a study reported SOC stocks or concentration up to 10 cm, the derived data set was added to 0–20 cm depth class for this analysis. The details of depth class and data points included are further elaborated in Appendix S3.

The SOC stock comparisons of soils with varying bulk densities and soil types to a depth class (0–100 cm) would imply unequal soil mass comparison whereas SOC stock investigation required the analysis of equivalent soil masses (Ellert and Bettany, 1995; Poeplau and Don, 2013). Mass correction, however, was not performed in our study because it would have involved comparison of paired sites and not chronosequence land-use change over the same site. The remaining studies reported C concentration as percentage (SOC concentration). In such cases, SOC_{stock} (Mg C ha^{-1}) was calculated as:

$$SOC_{stock} = SOC_{conc} \times BD \times D \quad (1)$$

where BD is the bulk density (g cm^{-3}) and D is the depth (cm).

In studies that only reported soil organic matter (*OM%*) or carbon concentration SOC_{conc}, the SOC_{stock} (Mg C ha^{-1}) was calculated by first calculating the SOC_{conc} as:

Table 3
Summary of the meta-analysis on ΔSOC% stock up to 40 cm depth across Forest-Agroforest-Agriculture/Pasture/Uncultivated Land continuum in different agroecological regions around the world.

Agroecological region	Agroforestry System (AFS) (ref. Table S17)	%ΔSOC stock				
		AFS vs. Agriculture	AFS vs. Forest	AFS vs. Pasture	AFS vs. Uncultivated land	# data points in meta-analysis
ASA Arid and semiarid	Agrisilviculture	–7.69	n.a.	72.5	n.a.	6
	Agrosilvopasture	20.2	–27.6	n.a.	n.a.	4
	Silvopasture	n.a.		28.1	n.a.	10
LHT Lowland Humid Tropics and subtropics	Multistrata syst.	24.1	12.6	n.a.	n.a.	25
	Agrisilviculture	33.6	–6.9	13.9	n.a.	39
	Agrosilvopasture	5.9	–6.8	–18.1	n.a.	16
	Silvopasture	n.a.	n.a.	40.01	22.6	11
MED Mediterranean	Agrisilviculture	17.1	n.a.	n.a.	n.a.	2
	Silvoarable	1.4	n.a.	n.a.	n.a.	12
	Silvopasture	n.a.	n.a.	–1.6	n.a.	2
TEM Temperate	Agrisilviculture	18.45	–14.7	n.a.	n.a.	19
	Agrosilvopasture	n.a.	n.a.	n.a.	– 45	4
	Silvopasture	n.a.	–15.5	n.a.	7.34	7

Note: Positive values indicate that SOC% was higher under AFS, and negative values indicate that SOC% was lower under AFS; n.a. = not available.

$$SOC_{conc} = 0.58 \times OM\% \quad (2)$$

where SOC_{conc} is the C concentration in soil (g 100 g^{-1} soil), OM% is the organic matter as a percentage of soil dry mass. This equation assumes that soil OM is 58% C (Mann, 1986).

For studies that did not report bulk densities, authors were communicated personally to provide the BD data or the BD were estimated following the equation suggested by Post and Kwon (2000):

$$BD = \frac{100}{OM\%/0.24 + ((100-OM\%)/1.64)} \quad (3)$$

2.3. Meta-analytical approach

We evaluated the effect-size based on the Response Ratio (*RR*) of SOC stocks. The response ratio, suitable for variables measured on a true ratio scale with a natural scale-unit and a natural zero point, quantifies the proportionate difference between the treatment mean (X_t) and the control mean (X_c) (Borenstein et al., 2009). To analyze changes in SOC stocks up to 100 cm depth for Agroforest vs. Agriculture or Agroforest vs. Forest or Agroforest vs. Pasture or Agroforest vs. Uncultivated Land, we calculated the response ratios as:

$$RR = X_t/X_c \quad (4)$$

To assess the relative impact of adopting AFS (either AFS vs. Agriculture/Forest/Pasture/Uncultivated Land on SOC stock, we considered AFS as the treatment group and Agriculture/Forest/Pasture/Uncultivated Land as the control group. The calculated response ratio thus quantified the percentage decrease or increase of soil carbon (Mg C ha^{-1}) between the two land management systems (AFS vs. Forest or Agriculture vs. AFS or AFS vs. Pasture). Since the *RR* must be log-transformed for statistical validation, all reported SOC stock values were log-transformed to achieve normality before conducting these analyses. The natural-log response ratio (*ln RR*) was calculated as:

$$\ln(RR) = [\ln(X_t) - ln(X_c)] \quad (5)$$

The corresponding sampling variance for each $\ln(RR)$ was calculated as:

$$V_{\ln(RR)} = S^2_{pooled}\left(\frac{1}{n_1(X_t)^2} + \frac{1}{n_2(X_c)^2}\right) \quad (6)$$

Weighted response ratio for each category was calculated from the RR of individual pairwise comparison between each AFS (treatment) and control (Agriculture/Forest/Pasture/Uncultivated Land) as:

$$\ln(RR)_w = \frac{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij} ln(RR)_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}} \quad (7)$$

where *RRij* is the j^{th} comparison (j = 1, 2, …, k) in the i^{th} group of AFS type (i = 1, 2, …, m). The standard error, (*SE*) of the *RR* weighed was calculated as:

$$SE(\ln(RR)_w) = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}}} \quad (8)$$

Where the weighting factor (w_{ij}) was estimated as:

$$w_{ij} = 1/Var(\ln RR) \quad (9)$$

Mean weighted effect size for each observation was calculated with 95% confidence intervals (*CI*). To facilitate interpretation, along with response ratio, percentage changes in soil organic carbon (ΔSOC%) stock was also considered, which was calculated as:

$$\Delta SOC\%\, stock = (\exp(ln\, RR_w) - 1) \times 100 \quad (10)$$

Analyses were performed with the packages *metafor* (Viechtbauer, 2010) and *ggplot2* (Wickham, 2017) and R version 3.4.0 (R Core Team, 2017). Random effect models are considered where the heterogeneity of true effect size among studies arises from random variation around the mean effect sizes of population studies. This allows different study specific effect sizes (Borenstein et al., 2009).

2.3.1. Meta-regression, ANOVA, linear mixed effect model and publication biases

In this study, we performed meta-regression (ANOVA), to assess the relationship between the moderator variables or covariates (Soil Depth, Agroecological region, Type of AFS nested within Agroecological region, and Age of management practices) and a dependent variable (SOC stocks in Mg C ha^{-1}). The Linear Mixed Effects model with four categorical factors (moderators): Depth, Agroecological region, Type of AFS nested within Agroecological region, and Age of management practices were considered separately for each control. Under the random/mixed effects model, for any predicted value there is a distribution of effect sizes.

The goal of the analysis was then to examine to what extent the moderators included in the model influence the size of the average true effect. In addition to testing the impact of moderators for statistical significance, it is important to quantify the magnitude of their relationship with effect size (Borenstein et al., 2009). For this purpose, index based on the percent reduction in true variance, analogous to the R^2 index was used with the primary studies The R^2 index, which is defined as the ratio of true variance which is the variance between studies explained to total true variance was used to quantify the proportion of variance explained by the covariates. In meta-analysis, the total variance includes both variance within studies and between studies. Only categorical variables were considered as covariates – a process known as dummy coding. Dummy Coding helps in assessing the impact of covariates and also predicts effect size in the studies included for this meta-analysis. The R^2 index in meta-analysis is computed as:

$$R^2 = \tau^2_{(1-unexplained)} / \tau^2_{total} \quad (11)$$

where $\tau^2_{unexplained}$ is the true variance unexplained and τ^2_{total} is the total variance in studies.

The reference categories are the categories that come first in alphabetic order. Standardized effect sizes were considered, giving greater weight to studies with low variance measures. A weight factor (1/variance = 1/ (τ^2 + v_i^2)) was used in the analysis. Residual heterogeneity (τ^2) were also accounted for each control using KN-HA parameters (Knapp and Hartung, 2003). Other detailed statistical treatment of the datasets included Logarithmic Transformation of data and Test for Asymmetry, Rosenthal's and Orwin's Fail Safe Number. Details of these are analyses are given in Appendix S1.

3. Results

The meta-analysis yielded results on changes in stock in different soil depth classes across Forest-Agroforest-Agriculture/Pasture/Uncultivated Land continuum in various different agroecological regions around the world. Statistically, when AFS were compared to other land-use systems, the Kendall rank correlation test for publication bias and the regression test with standard errors as predictors in a meta-analytic model did not indicate any significant bias (Appendix S1, Fig. S10–S13). Furthermore, the funnel plot was fairly symmetric and the QQ plot did not show any significant departure from normality, neither the Kendall rank correlation test nor the regression test for publication bias indicated any bias (Appendix S1, Tables S4, S8, S12, S16).

Out of the 78 publications included for this study, 95% studies reported BD while only 5% of the studies did not report BD, which was retrieved by person communication with the authors or by using Eqs. (2) and (3).

The results are rather voluminous such that all of them cannot be presented here due to space limitations. A summary of ΔSOC stock up to 40 cm soil depth for all land-use systems combined in different regions is presented in Table 3, and a similar summary ΔSOC stock up to 60 cm

Table 4
Summary of the meta-analysis on ΔSOC% stock up to 60 cm depth across Forest-Agroforest-Agriculture/Pasture/Uncultivated Land continuum with respect to major agroforestry systems in different agroecological regions around the world.

Agroecological region	Agroforestry System (AFS) (ref. Table S17)	%ΔSOC stock			
		AFS vs. Agriculture	AFS vs. Forest	AFS vs. Pasture	# data points in meta-analysis
ASA (Arid and semiarid)	Agrisilviculture	–9.9	n.a.	29.5	13
	Silvopasture	n.a.	n.a.	16.3	8
LHT (Lowland Humid Tropics and subtropics)	Multistrata syst.	40.6	20.4	n.a.	35
	Agrisilviculture	–9.3	n.a.	3.8	20
	Silvopasture	n.a.	n.a.	–3.0	8
MED (Mediterranean)	Silvoarable	8.5	n.a.	n.a.	7
TEM (Temperate)	Agrisilviculture	n.a.	–10.8	n.a.	3
	Silvopasture	n.a.	n.a.	–2.7	4

Note: Positive values indicate that SOC% was higher under AFS, and negative values indicate that SOC% was lower under AFS; n.a. = not available.

depth across Forest-Agroforest-Agriculture/Pasture/Uncultivated Land continuum with respect to major agroforestry systems is presented in Table 4. Further, a summary of percentage changes in soil organic carbon ΔSOC% stock between AFS vs. Agriculture/Forestry/Pasture in four soil depth classes (0–20, 0–40, 0–60, and 0–100 cm) in the three agroecological regions is presented as Fig. 2. Other results are presented in Appendix and as supplementary information. Salient aspects of the results of comparison of ΔSOC%stock for AFS vs. Agriculture/ Forest/ Pasture are summarized below. The ΔSOC%stock for AFS vs. Uncultivated lands comparison had low numbers of data points and did not show any consistent trend; those results are therefore not reported in the text; however, they are included in the summaries (Table 3, Fig. 2).

3.1. AFS vs. Agriculture

Comparison of AFS vs. Agriculture showed that, in general, percentage in SOC% stock increased under AFS across all agroecological regions and depth classes. Outliers or exceptions to this general trend were noted only in a few cases with smaller sample sizes.

Within the 0–20 cm depth class, the highest SOC% stock was noted under Silvopastoral systems in LHT region (151.6%) (Fig. 1b), followed by Silvoarable Systems in the MED region (52.5%: Fig. 1c). In the 0–40 cm depth profile, AFS vs. Agriculture showed substantial improvements in SOC% stock with the highest percentage under Agrisilviculture and Multistrata Systems in the LHT region, 33.6% and 24.1% respectively (Table 3). Overall, the LHT region showed SOC% higher stock under all depth classes up to 100 cm (Fig. 2). The Silvoarable systems in the MED region showed the lowest SOC% (1.4%: Table 3). The results showed an increase in SOC% stock (40.6%) in the 0–60 cm depth class under Multistrata Systems in the LHT region (Table 4), and 48% increase in the 60–100 cm depth class (Appendix S1, Fig. S6b). However, SOC stocks under ASA and LHT Agrisilviculture systems was lower, compared to Agriculture, in the 0–60 cm depth class by 9.9% and 9.3% respectively (Table 4). In the 0–100 cm soil depth, higher SOC% stock was noted under AFS vs. Agriculture systems (Multistrata Systems: +17.9%; Agrisilviculture system: +36.8% LHT; and Silvopasture; +8.8% MED; (Appendix S1, Fig. S4b, S4c).

3.2. AFS vs. Forest

The comparison of AFS vs. Forest showed a general trend line of lower SOC% stock under AFS across most agroecological regions and depth classes (Tables 3 and 4, Fig. 2). with the exception of Multistrata systems in LHT that reported higher SOC% (12.6% and 20.4%) up to a depth of 40 cm and 60 cm respectively (Tables 3 and 4). Similar trends were also noted within the 0–60 cm depth where SOC% for Agrisilviculture vs. Forest was lower (−26.8%: Appendix S1, Fig. S3) while Multistrata Systems vs. Forest had higher SOC% (+9.3%) under AFS, (Fig. S3b), within the LHT region. In the 0–100 cm depth, AFS vs. Forest reported higher SOC% stock under Multistrata systems and Agrosilvopasture, while Agrisilviculture had a decline (–26.8%; LHT: Appendix S1, Fig. S4b). In the MED region, Silvopasture showed a higher SOC% by 56.1% over Forest within 0–100 cm (Appendix S1, Fig. S4c).

3.3. AFS vs. Pasture

Comparing AFS vs. Pasture showed varying trends in SOC% stock improvements across different agroecological regions and depth classes, especially in the tropics. In the top soil (0–20 cm), the ASA region showed higher SOC% stock across Agrisilviculture (+15%), Agrosilvopasture (+12.8%) and a higher SOC stock of +89.4% in the Silvopasture systems (Fig. 1a). The increment was only marginal (+2.2%) under Silvopasture in the TEM region. In the LHT region, SOC stocks were lower under all AFS practices; the Silvopasture systems within MED region too reported lower SOC% stock (–9.2%) in the top soil (Fig. 1c). The trend was, however, reversed, down the soil profile (0–40 and 0–60 cm), where Agrisilviculture and Silvopasture systems continued to show higher SOC% stock over Pasture. On the other hand, in the 0–100 cm depth, the percentage changes in soil organic carbon (ΔSOC%) stock were higher under Silvopasture systems within ASA and MED regions by 27.1% and 22.7% respectively (Appendix S1, Fig. S4). Overall, the results for AFS vs. Pasture varied across agroecological regions, with ASA being the region with the highest SOC% stock improvements.

3.4. SOC stocks under AFS with varying age of system

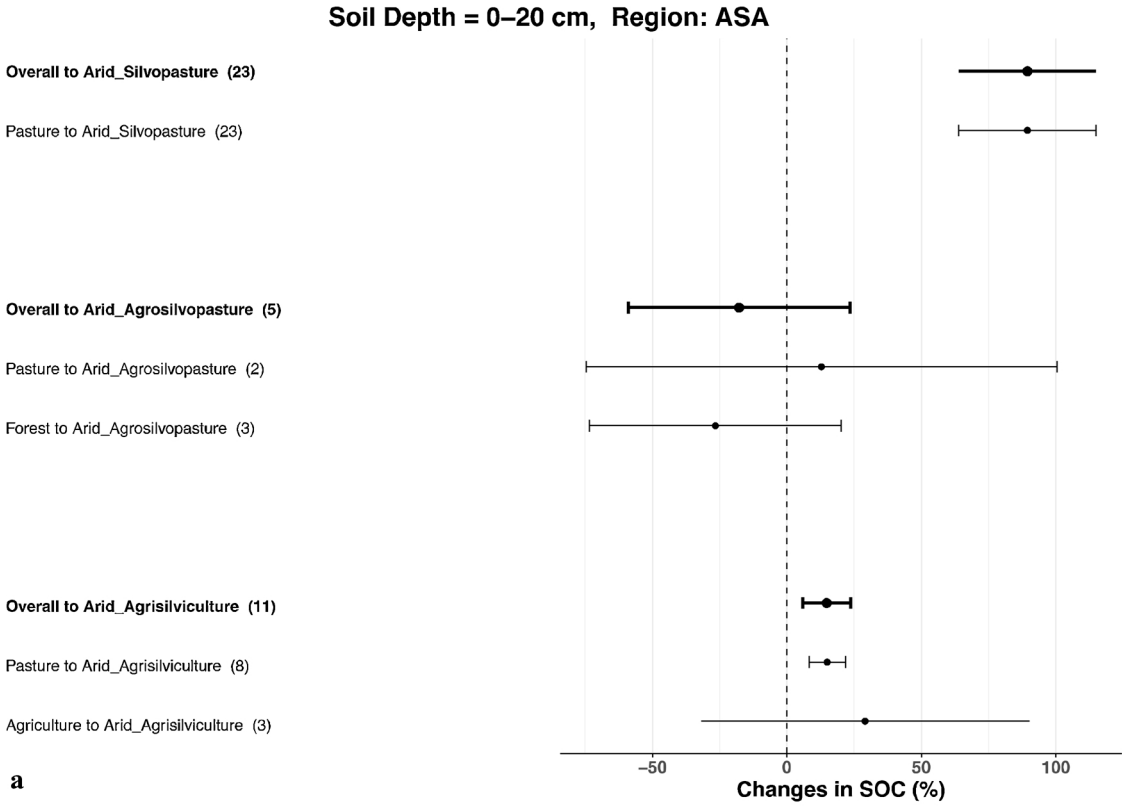
The effects of the duration (age) of AFS management practices on SOC stock under each agroecological region and specific soil depth classes are elaborated in the following section. A summary of %ΔSOC stock between Agroforestry systems (AFS) of varying age groups is shown in Fig. 3.

3.4.1. Age group: 0–5 years

Overall, SOC% stocks were higher in the top soil (0–20 cm) under AFS compared with other land-use systems during the first five years of establishment of AFS in all agroecological regions. The differences in soil organic carbon under AFS compared with Pasture were 15.7% in ASA, 3.5% in LHT, and 5.6% in the MED region; compared with Agriculture, AFS had 9.3% SOC higher stock in LHT (Appendix S1, Fig. S7b) and 6% in TEM region (Appendix S1, Fig. S7d). On the other hand, comparing AFS with Forest, the SOC% stock was lower in AFS in the 0–40 cm depth: 21.1% in ASA, 24.3% in LHT, and 12.8% in TEM. In the 0–60 cm soil-depth class, overall SOC stock under AFS in the ASA region was higher by an average of 8.55% compared to agricultural systems during the 0–5 years. In LHT, overall, AFS between 0–5 years had higher SOC% stocks by 9.7%. In TEM region, AFS vs. Forest comparisons showed lower SOC% in AFS by 10.8% (Appendix S1, Fig. S9). In the 0–100 cm soil layer, SOC% was higher by 19.1% under AFS vs. Agriculture in LHT.

3.4.2. Age group: 5–10 years

In the ASA region, AFS aged between 5–10 years, compared with other land-use systems, reported higher SOC% by 18.1% overall in the



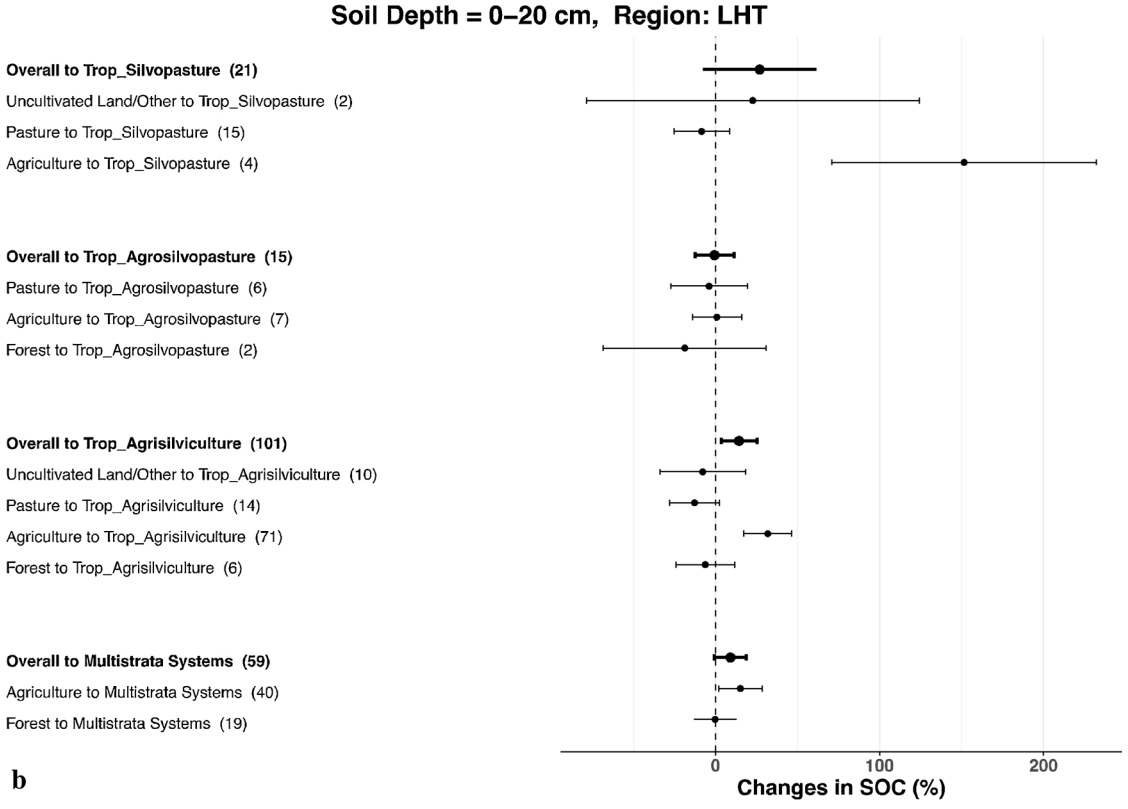


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Fig. 1. Percentage changes in soil organic carbon stock (0–20 cm) between agroforestry systems when compared to forest or agricultural land-use or pastures in the ASA region (Agroforest vs. Agriculture, Forest vs. Agroforest, Agroforest vs. Pasture). The numbers in parentheses indicate the number of observations The square in the center indicate the mean. The whiskers indicate the 95% confidence interval of ΔSOC% values. (b) Percentage changes in soil organic carbon stock (0–20 cm) between agroforestry systems when compared to forest or agricultural land-use or pastures in the LHT region (Agroforest vs. Agriculture, Forest vs. Agroforest, Agroforest vs. Pasture).The numbers in parentheses indicate the number of observations The square in the center indicate the mean. The whiskers indicate the 95% confidence interval of ΔSOC% values. (c) Percentage changes in soil organic carbon stock (0–20 cm) between agroforestry systems when compared to forest or agricultural land-use or pastures in the MED region (Agroforest vs. Agriculture, Forest vs. Agroforest, Agroforest vs. Pasture). The numbers in parentheses indicate the number of observations The square in the center indicate the mean. The whiskers indicate the 95% confidence interval of ΔSOC% values. (d) Percentage changes in soil organic carbon stock (0–20 cm) between agroforestry systems when compared to forest or agricultural land-use or pastures in the TEM region (Agroforest vs. Agriculture, Forest vs. Agroforest, Agroforest vs. Pasture). The numbers in parentheses indicate the number of observations The square in the center indicate the mean. The whiskers indicate the 95% confidence interval of ΔSOC% values.

soil depth class 0–20 cm. Typically, AFS vs. Pasture comparisons demonstrated higher SOC by 60.5% under AFS while compared with Forests, the SOC% stock under AFS was lower by 26.5% (Appendix S1, Fig. S7). In the LHT, overall, AFS had higher SOC% stocks by 27.5%. In other regions, the percentage changes in soil organic carbon were less noticeable. In 0–40 cm depth, overall, in the ASA and LHT region, SOC% under AFS were higher by 3.4% and 12.19% respectively during 5–10 years. (Appendix S1, Fig. S7). In the 0–60 cm depth class, SOC% stock under AFS compared with Pasture was higher by 28.2%, and by 27.8% against Agriculture in the ASA (Appendix S1, Fig. S8).

3.4.3. Age group: 10–20 years

Comparatively, SOC% stock was higher under AFS with increasing age of systems. Overall, under the 10–20 years old AFS, SOC% stocks were higher by 73.3% over Pasture land in the top soil 0–20 cm. In LHT region, SOC% stocks under AFS was 31.6% higher than under Agriculture. Compared with Forest, however, SOC% was 27.5% lower under AFS (Appendix S1, Fig. S7). In the TEM region, SOC% stock under AFS was 8.6% higher compared to Pasture. In MED region, AFS had 40.1% had higher SOC% stock than Agriculture, while compared to Forest, it was lower by 47.9% (Appendix S1, Fig. S7). In the 0–40 cm depth, the ASA region reported a significantly higher SOC% (71.03%) when AFS was compared to Pasture land (Appendix S1, Fig. S8). In the 0–60 cm depth, the comparison of AFS vs. Pasture showed a higher SOC% stock by 28.21% and 19.6% in the ASA and TEM region respectively. AFS vs. Agriculture practices in the LHT and MED regions reported higher SOC% stock by 40.1% and 7.7% respectively (Appendix S1, Fig. S9). In the soil profile 0–100 cm, AFS over Pasture had higher SOC% stock of 27.1% and 53.1%, for ASA and LHT regions, respectively. AFS over Agriculture had higher SOC% stocks by 55%, while compared to Forest, AFS had higher SOC stock by 3% in the 0–100 cm depth.

3.4.4. Age group: > 20 years

In the top soil profile, within the LHT region, SOC% stock was higher by 4.3% (Appendix S1, Fig. S7) overall. In the TEM region AFS had a 27.8% lower in SOC% stocks in when compared to Uncultivated Land after > 20 years (Appendix S1, Fig. S7). Within the 0–40 cm depth in the LHT region, SOC% stocks were higher by 7.2%. Comparisons of AFS to Agricultural land and Forests showed SOC stocks were higher by 9.1% and 19.1% respectively. Comparing AFS vs Pasture in the TEM region, SOC% was higher by 22.2% under AFS, and in the MED region, AFS compared with single species Agriculture, the SOC% was higher by 9.6% increase of (Appendix S1, Fig. S7).

3.5. Mixed effect models, meta-regression and ANOVA

Linear mixed effect models with four categorical covariates (moderators) (i) Depth, (ii) Agroecological region, (iii) Type of AFS nested within agroecological region, (iv) Age of AFS management system, were analyzed individually for comparisons of Forest vs. Agroforest, Agriculture vs. Agroforest, Pasture vs. Agroforest, and Uncultivated land vs. Agroforest. (Appendix S1, Tables S3, S7, S11, S14). The results of analyses of Mixed Effects Model and meta-regression individually with Agriculture, Forest, Pasture, and Uncultivated Land, showing detailed results of tests for heterogeneity are summarized in Table 5.

4. Discussion

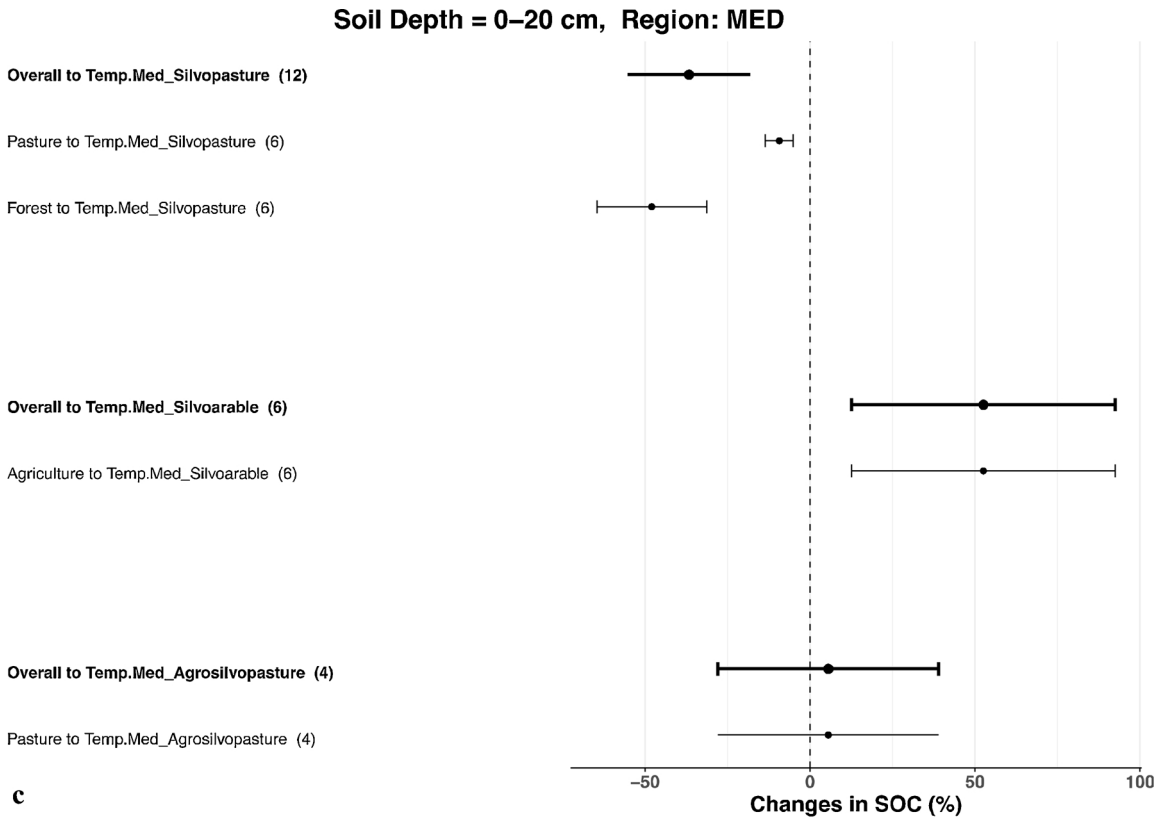
This meta-analysis consisting of 858 data points (sites) extracted out of 78 peer-reviewed publications from around the world and covering comparisons of Agroforestry vs. Agricultural, Forestry, Pasture or Uncultivated Land represents a detailed effort in quantitatively assessing the impact of agroforestry systems on SOC% stocks. Ideally, in order to comprehend the influence of different land-use systems on SOC, it is important to consider both SOC stocks and concentrations; using only one of these might cause a bias in assessing the treatment effect. However, it is widely accepted that if only one measure is to be considered, then SOC stocks give a more accurate estimation, and in our dataset, About, 95% of the studies reported SOC stocks (Mg C ha^{-1}). Additionally, SOC stocks can be used to estimate the SOC sequestration potential (Mg C ha^{-1} yr^{-1}) of AFS. Therefore, SOC stock was the chosen measure for the purpose of this meta-analysis.

4.1. SOC stock changes under agroforestry systems across agroecological regions

4.1.1. AFS vs. Agriculture

Overall, SOC stocks were higher under AFS compared with Agricultural systems across agroecological regions, which indicates that AFS, in general, have distinct advantage over monocrop systems in terms of soil C storage. The Mixed Effects model, run as a meta-regression model, showed that the effect sizes of SOC stocks for the AFS vs. Agriculture comparison were significantly differed from zero. This means that the results are rigorous, devoid of publication biases. Furthermore, the agroecological region turned out to be a significant covariate that influenced SOC stocks (Appendix S1), confirming that SOC stock increase varies across regions. For example, SOC stocks was higher by 26% up to 100 cm in the LHT region while the higher SOC stocks under AFS over Agriculture in the MED region was reported to be 5.8% in the same soil-depth class (Figs. 1b, 2, Appendix S1, Fig. S3). Repeated input of hedgerow pruning from woody hedgerow species to the alleys in tropical alley cropping, and leaf-litter addition form overstory woody species are the main source of biomass addition to soils in Tropical Agrisilviculture compared to Agricultural systems under similar conditions (Cardinael et al., 2012). Minimum (or no) tillage could be another possible reason for the higher SOC stocks under Tropical Agrisilviculture (Oelbermann et al., 2006; Schroth and Zech, 1995).

Multistrata systems, which include shaded perennial AFS and tropical homegardens in the LHT region, store substantially high amount of SOC stocks even in deeper layers of soil (Abou Rajab et al., 2016; Gama-Rodrigues et al., 2010; Monroe et al., 2016; Saha et al., 2010). These multistrata AFS render ecosystem services with high value for supporting human livelihoods including but not limited to soil carbon storage (Millennium Ecosystem Assessment, (MEA, 2005; Nair, 2017). Our results showed that overall, the multistrata systems stored 48% higher SOC stocks compared to monoculture Agriculture (Fig. 1b,



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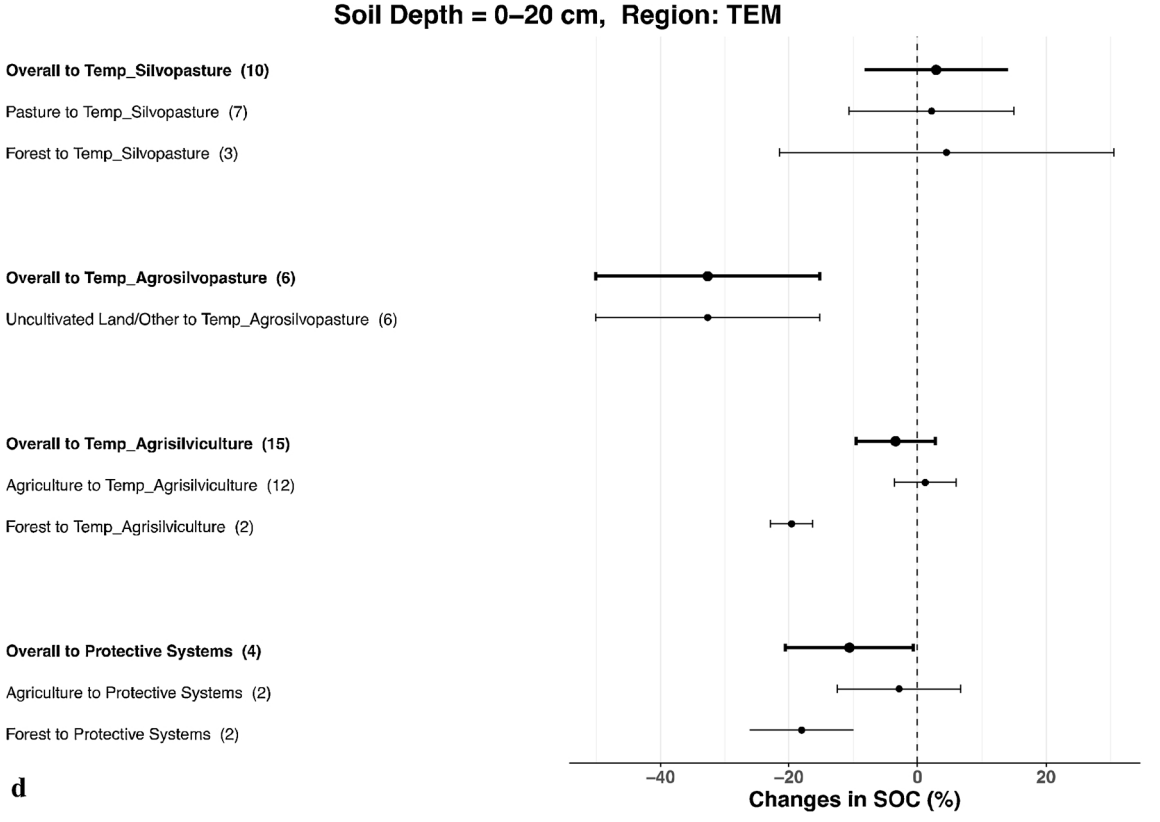

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Fig. 1. (*continued*)

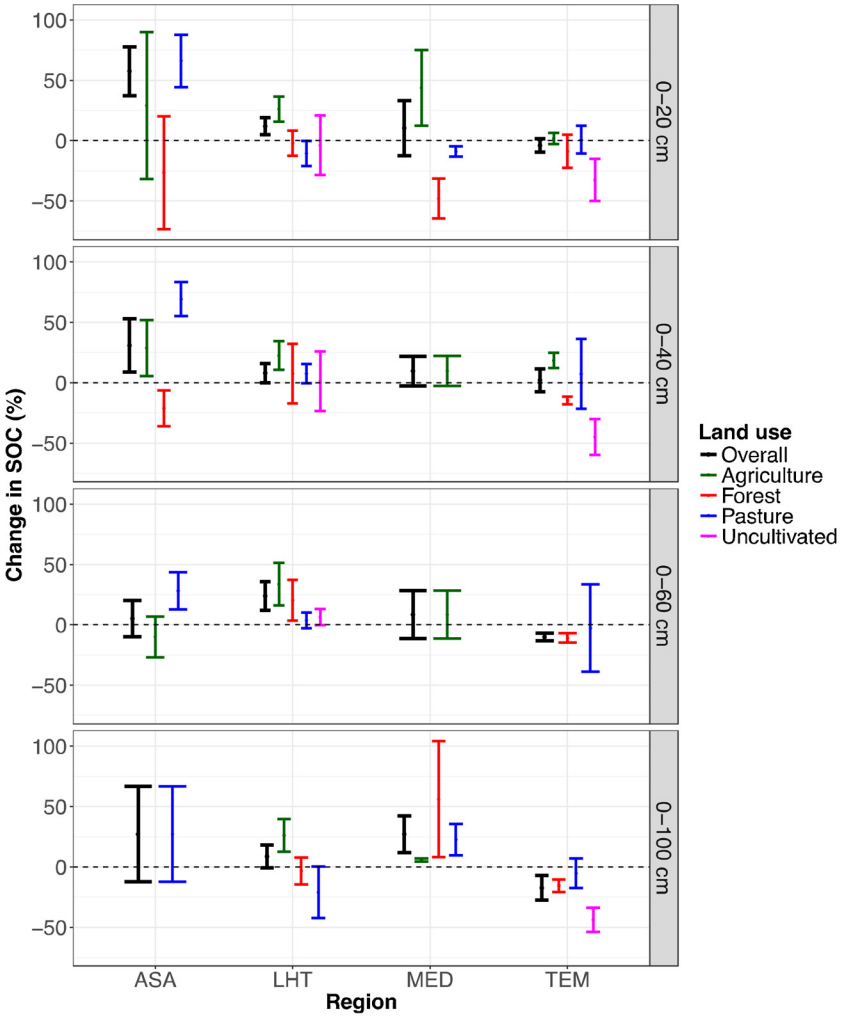

Fig. 2. Summary of results of a global meta-analysis showing %ΔSOC stock between Agroforestry systems (AFS) vs. Agriculture/Forestry/Pasture/Uncultivated Land in four soil depth classes (0–20, 0–40, 0–60, and 0–100 cm) in ASA, LHT, MED and TEM regions around the world. The analysis was based on 858 data points derived from 78 publications in international peer-reviewed journals.

Appendix S1, Fig. S2b, S3b, S4b), and were efficient and the most consistent AFS in storing SOC stocks at all soil depth classes up to 100 cm depth, especially in the 60–100 cm depth. It is worth noting that the relative changes in SOC% stocks were substantially higher under Agrosilvoarable systems in the Mediterranean region, ranging from 52.5% in the top soil to 8.5% in the deep soil. Similar results were also reported by (Burgess et al., 2005; Cardinael et al., 2015, 2017; Upson and Burgess, 2013; Upson et al., 2016). In the TEM region, our analysis showed that SOC stocks of Agrisilviculture (alley cropping systems) was higher by 18.4% over Agriculture, which is in accordance with results reported by Cardinael et al., 2012, 2015, 2017; Pardon et al., 2017; and Wotherspoon et al., 2014.

4.1.2. AFS vs. Forest

Comparing AFS vs. Forest, the SOC% stocks were lower in AFS across almost all depth classes and all agroecological regions, the highest being in the MED region (−47.9%) in the upper 0–20 cm, and the least in the LHT region (−2.1%). It is a well-accepted that deforestation leads to loss in SOC stocks. This was evident in our study as well. The forests retain major proportion of SOC in the topsoil, thus land-use change causes losses in SOC% stocks especially in the top soil (Guo and Gifford, 2002; Leuschner et al., 2013); similar trends were also reported in the analysis by De Stefano and Jacobson (2017). This observation was further strengthened by the Mixed Effects Models with Forest as control, where Depth of soil was a significant covariate to SOC stock changes upon deforestation.

Additionally, the type of AFS nested within agroecological region was also a significant covariate to SOC stock changes upon deforestation This can be explained with the example of SOC stocks under Multistrata Systems in LHT region. Multistrata systems, like shaded perennial AFS, have been recognized for substantially higher soil-carbon storage potential than conventional monoculture systems (Abou Rajab et al., 2016; Gama-Rodrigues et al., 2010; Norgrove and Hauser, 2013; Soto-Pinto et al.,2010) and are rated as comparable to secondary forests as they often “mimic” forest-like environment (Beer et al., 1998; Tscharntke et al., 2011). This analysis showed that between Forest and Multistrata systems, the difference in SOC between the two, up to 100 cm depth, was practically very little (3.4% lower in Multistrata system). The litterfall is the main source of C addition to soil in such systems, the extent of which depends on the type of the shade tree as well as the shaded species. Among the three-major Multistrata Systems, perennial species of coffee (*Coffea* spp.), cacao (*Theobroma cacao*), and tea (*Camellia sinensis*), the litterfall is much lesser for tea, estimated at 3.28 Mg $ha^{-1}yr^{-1}$ (Paudel et al., 2015); for coffee, it could range from 3.3 to 6.3 Mg $ha^{-1}yr^{-1}$ (Celentano et al., 2011); and for cacao as high as 10 Mg $ha^{-1}yr^{-1}$ (Beer, 1988). But given that these Multistrata systems have similar fine-root production and turnover rates as for forests (Hertel et al., 2009; Tscharntke et al., 2011), the combined root litter C flux to the soil from the understory (shaded) species and the overstory shade tree could be comparable to or even higher than that under

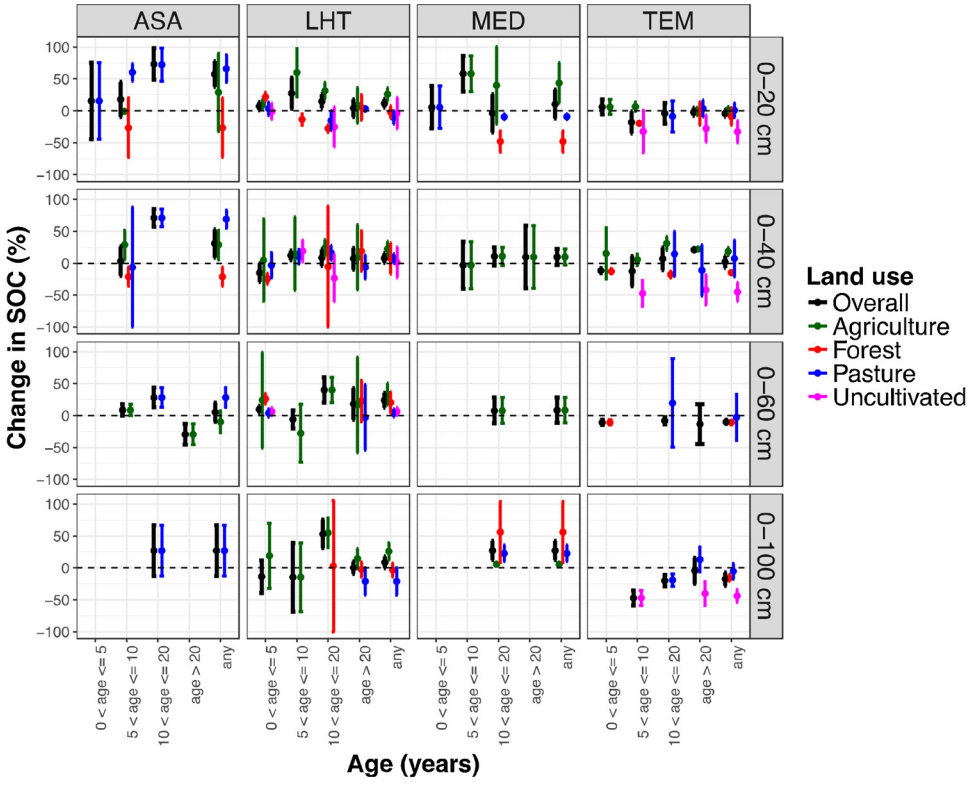

Fig. 3. Summary of results of a global meta-analysis showing %ΔSOC stock between Agroforestry systems (AFS) of varying age groups vs. Agriculture/Forestry/Pasture/Uncultivated Land in four soil depth classes (0–20, 0–40, 0–60, and 0–100 cm) in ASA, LHT, MED and TEM regions around the world.

Table 5
Summary Results of Statistical Analyses: *Mixed Effect Models, Meta-regression ANOVA*.

Parameters/ Descriptors	Control for Mixed Effect Models: AFS vs.			
	Agriculture	Forest	Pasture	Uncultivated land
Test for heterogeneity	Significant Q = 24614 df = 375 *p*-value < .0001 τ^2 = 0.12 R^2 = 7.65%	Significant Q = 32,429 df = 114 *p*-value < .0001 τ^2 = 0.07 R^2 = 14.5%	Significant Q = 6947 df = 233 *p*-value < .0001 τ^2 = 0.05 R^2 = 52.13%	Significant Q = 823 df = 65 *p*-value < .0001 τ^2 = 0.2 R^2 = 19.48%
Categorical variables	(i) Depth, (ii) Agroecological zone (Region), (iii) Type of AFS nested within Climatic zone (Region: Type of AFS), (iv) Age of AFS management system	i) Depth, (ii) Agroecological zone (Region), (iii) Type of AFS nested within Climatic zone (Region: Type of AFS), (iv) Age of AFS management system	i) Depth, (ii) Agroecological zone (Region), (iii) Type of AFS nested within Climatic zone (Region: Type of AFS), (iv) Age of AFS management system	(i) Depth, (ii) Agroecological zone (Region), (iii) Type of AFS nested within Climatic zone (Region: Type of AFS), (iv) Age of AFS management system
Depth	p = 0.36	p = 0.02	p = 0.002	p = 0.06
Region	p = 0.0005	p = 0.8	p < 0.038	p = 0.0006
Region: Type of AFS	p = 0.0065; Arid Silvopasture, p = *0.0002*; Tropical Agrisilviculture, p = 0.0012; Tropical Agrosilvopasture, p = 0.0001	p = 0.02	p < 0.001; Arid Silvopasture, p < 0.001; Tropical Agrosilvopasture, p < 0.001	p = 0.03; Tropical Agrisilviculture, p = 0.012
Age of Management	p = 0.010	p = 0.4	p = 0.59	p = 0.017

forest, as reported from studies in Brazil and Indonesia (Gama-Rodrigues et al., 2010; Hertel et al., 2009; Monroe et al., 2016); this is corroborated by our analysis, which reported increase in SOC stocks by 34.4% compared to Forest between 60–100 cm (Appendix S1, Fig. S3).

4.1.3 AFS vsvs. Pasture

Establishment of AFS over Pasture requires site preparation for planting trees and introducing livestock. These land management practices could potentially reduce SOC stocks in some cases (Guo and Gifford, 2002). Comparing AFS vs. Pasture, SOC stocks under AFS was higher in the ASA region from 66.2% in the top 20 cm and 27% in deep soils (up to100 cm) (Fig. 1a, Appendix S1, Fig. S2). However, in TEM and LHT regions, SOC stocks declined with increased depth by 5.3% and 21% respectively. Thus, silvopastoral systems might be more efficient in improving SOC stocks in ASA than TEM and LHT region.

Lower SOC stock in silvopastoral systems compared to adjacent pasture have been reported before (Seddaiu et al., 2013). In pastures, the annual turnover from rhizodeposition, which increases the SOC stocks, is much higher than under trees (Jobbágy and Jackson, 2000). Introducing

leguminous plants often increases soil nitrogen, enhances fertility and improves belowground productivity, and consequently helps build up higher SOC stocks (Boddey et al., 2010; Conant, 2010). Thus, planting trees within a pasture might not substantially improve SOC stocks due to "soil carbon saturation" of pastures which is already at a threshold SOC level (Hassink, 1994, 1997) in certain agroecological region like TEM.

4.1.3. AFS vs. Uncultivated land

In majority of the cases, the category of Uncultivated/Land included Fallow land, and land-use types which were not defined as Forest/Pasture/Agriculture. Agrisilviculture systems like Improved Fallows were primarily "designed" for and promoted in temperate, tropical and arid region (Buresh and Cooper, 1999) where degraded soils are a major constraint to improving traditional agricultural practices (Sanchez, 1999, 2002). Improved fallows have yet to prove their worth in the temperate region because the long dry season in those regions limits the growth and nitrogen fixation potential of the fallow species. Fallows also do not perform well in shallow soils, poorly drained ones, or frost-prone areas (Sanchez, 2002). These AFS are effective for improving nutrients but fall short to significantly increase SOC stocks (Buresh and Cooper, 1999; Kaonga and Coleman, 2008). Additionally, phosphorus (P) in soil is also a limiting factor in N_2 fixation in poor soil which inhibits SOC stock improvement by reducing belowground productivity (Boddey et al., 2010; Conant et al., 2001).

4.2. SOC stocks in relation to age of trees in AFS management practices

Studies on changes in SOC content following change in land management practices and age of trees have reported conflicting results, some indicating increase in SOC content with stand age (Berthrong et al., 2009), while others had contrary results, especially in early duration after afforestation (Laganière et al., 2010). Ideally, land-use changes from Agriculture to AFS should affect the surface soil layer consistently across age of stand/trees; however, a majority of studies have found that the SOC stocks to decline initially, and then increase with increase in stand age (Chen et al., 2005). A cross section of these contrasting results was found in our analyses too that age of trees in AFS influenced SOC stocks changes differently under different agroecological regions (Appendix S1). The discussion here is limited to influence of tree age on SOC stocks in comparisons between AFS vs. Agriculture or Pasture because transformation of Forest to any other land use (including AFS) is known to cause SOC stocks declines and age of trees *per se* may not have a substantial role in it.

In our analysis, in ASA region, older AFS reported higher SOC% stocks in the top soil. In deeper soil layers (up to 100 cm), AFS aged between 10–20years reported higher SOC stocks (27.3%), (Appendix S1, Fig. S7). We did not have sufficient data points under managed AFS > 20 years for cumulative analysis. In the LHT region, maximum change in %SOC stocks (range: 14.9% in top soil to 55% in deep soil) was in systems aged between 10–20years. Systems aged > 20 years showed higher SOC% stocks ranging from 4.4% in the top soil to 14.5% in deep soil. Other results did not show any consistent trend. Establishment of AFS involves the introduction of varying species and structural arrangement which could affect SOC stock accumulation differently, i.e. management practices of similar age group can affect SOC stocks differently as trees species interacting with land-use change alters SOC differently (Bárcena et al., 2014; Nair et al., 2011). The available results from this analysis seem to be inadequate to draw rigorous (convincing) conclusion on the effect of tree management and age on SOC stock changes under AFS across various agroecological regions. There is a need to monitor SOC stock changes in greater detail within and beyond the first decades after land-use change and determine the time required for AFS to improve SOC stocks significantly.

4.3. SOC stock changes and the Forestry – Agroforestry – Agriculture/Pasture continuum

It is a common perception that conversion of Forest to any other land management practices will result in land degradation in general and decrease in SOC stocks in particular. Nair et al. (2009) proposed "forest > agroforest > monoculture and arable crops" as the general sequence in terms of SOC stock decline. This trend was observed across all AFS in our analysis. The only exception was in the case of AFS vs. Pasture management practices. Even though AFS vs. Pasture positively affected SOC stocks under AFS in the ASA region, AFS had lower SOC stocks in TEM region than in Pasture. It is not unusual to find higher SOC stocks in pasture than AFS or even forests. Guo and Gifford (2002) and Post and Kwon (2000) reported that when forests were replaced by pastures, the considerable loss of aboveground biomass did not necessarily imply loss or decline in SOC. Indeed, pasture established under previously forested areas could have greater potential to store carbon in soil. Further, there could be "soil carbon saturation" in pasture as explained by Hassink (1997). According to our analysis, AFS significantly affected SOC stocks even up to 100 cm soil depth (0–100 cm). Thus, this study provides a rigorous statistical, global validation of individual results reported by numerous studies that incorporating trees on land leads to increased soil carbon stocks (Haile et al., 2010; Howlett et al., 2011; Montagnini and Nair, 2004; Nair et al., 2009; Saha et al., 2010; Nair et al., 2010). The extent of such AFS-induced SOC storage, however, varies significantly across agroecological region, age of management practices, and depth of soil, in addition, naturally, to obvious effects of local climatic and soil conditions.

It is worth noting that incorporation of trees into agricultural land or pasture led to increase in SOC stocks in all agroecological regions except the TEM region. This observation from the TEM region could be attributed to C saturation in soil as reported by Wiesmeier et al. (2015); Stewart et al. (2007), and Hassink (1997). According to Stewart et al. (2007), the SOC storage may be increased directly by increasing C returns to the soil but the amount of C that can become associated with clay and silt particles is limited. This suggests an upper limit, or saturation limit to whole soil. The smaller increase in SOC content with increased C input level is due to the decreased capacity of a high C soil to store added C. Additionally, this soil C saturation is more prominent in grassland/pasture as they generally have higher C content than cultivated arable soils, due to the higher incorporation of organic C and the absence of soil tillage. In our meta-analysis, 59% of the studies used from TEM were grassland soils (silvopasture and agrosilvopasture: Table 1). It is likely that in those sites in the TEM region, the soil had already reached, or was close to reaching, C saturation and the additional C input did not cause significant improvement in SOC accumulation.

4.4. Data quality and methodological challenges

It is important to recognize the deficiencies of the available datasets on SOC stocks in AFS, upon which the analysis was based. As detailed by Nair (2012), AFS, by their very nature, are extremely site-specific, and are characterized by high variability in site-specific features such as soil type, plant species and density, and management practices. The difficulties arising from this diversity and complexity are confounded by the heterogeneity caused by lack of standardized methodologies, and sometimes failure to follow even available ones. Another serious issue of concern is that some studies do not report the important parameters such as soil bulk density, and the methods followed in sampling and analysis of soils and computation of data. Furthermore, differences in SOC stock improvement on adopting AFS are also attributable to the intrinsic properties of soil such as soil type, mineralogy, clay content, texture, and land-use history. Thus, adaptation of a specific AFS over Agriculture does not necessarily guarantee improvement of SOC stocks and could be regarded as case specific. The extent of seriousness of these deficiencies of the study and their impact on the results presented

cannot be gauged at this stage. During the past three decades, studies investigating C stocks under agroforestry pointed out methodological challenges related to sampling, analysis, computations, and interpretation of results (Nair, 2011). Agroforestry systems are characterized by high variability in site-system features, soil type, tree species and management practices pertaining to geographical locations, which produced an inconsistent estimate of agroforestry C stocks (Montagnini and Nair, 2004; Nair, 2012, 2011). Lack of standardized methodologies may increase the heterogeneity of dataset, and assessment of the consistency of effects across studies is an essential part of meta-analysis.

All of the above-mentioned challenges were encountered during the meta-analysis data collection and analyses, especially issues related bulk density and missing SD, SE and variances. For the studies that we used in the analysis that had not reported BD, the information was obtained by contacting the authors who graciously obliged to provide the data. The lack of clear and complete data about the processes associated with C dynamics and storage resulted in unrestrictive criteria for data inclusion, leaving out some potentially important variables, such as soil clay content. As suggested by Nair (2011, 2012), more accuracy in description of how the data were collected, analyzed, and managed is needed. A unified methodological approach will surely benefit future agroforestry research.

5. Conclusions

Our analysis showed evident trends of differences between AFS and other land-use systems (Agriculture, Forestry, and Pasture) in terms of SOC stocks across various agroecological regions. Overall, while SOC stocks were higher under AFS compared with sole-crop agricultural systems under comparable conditions, the stocks were generally higher under Forestry. Comparing AFS vs. Agriculture, Multistrata systems in the lowland humid region were highly effective in increasing SOC stocks in soils even up to 100 cm depth, while Silvoarable systems were effective in improving SOC stocks in the Mediterranean region. The AFS vs. Pasture comparisons demonstrated that AFS like Silvopasture and Agrosilvopasture were effective in improving SOC stocks in the arid and semi-arid regions, but not so in the temperate regions. Thus, the effect of AFS on SOC stock improvement is variable under different agroecological regions. The result that the likely additional C input via AFS did not improve SOC stocks in the TEM region suggests that the potential role of AFS in climate-change mitigation through SOC stock improvement could be more relevant in the tropical regions, where the soils are known to be C-depleted than in the C-saturated temperate regions. The advantage of adopting AFS depends also on the age of management practices, systems aged between 10–20 years being considerably more effective in improving SOC stocks than the relatively juvenile systems of less than 10 years of age. Given that rigorous studies undertaken under a variety of land-management scenarios on this aspect are limited, we believe this comprehensive analysis provides a much-needed impetus for detailed studies of this nature in the future.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2018.07.014.

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